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A study on effect of temperature on magnetic memory parameters

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The paper presents a theoretical and experimental investigation on the effect of temperature variation on magnetic core memory design parameters. The temperature problem in a ferrite core memory arises due to the energy that is applied for switching the cores. The switching coefficient is the sum of two independent effects—one due to the eddy current and other due to the spin relaxation effect. These contributions are studied individually as functions of temperature. Experimental results are presented briefly and used as a guide to the determination of optimality criterion for designing optimum magnetic core memories.

1. INTRODUCTION

The most important requirements of a good magnetic material for fast, reliable, random access core memory are a good squareness ratio and a good thermal stability. In this paper theoretical and experimental investigations on these important criteria are presented. The toroidal cores used in memory systems are very much sensitive to temperature, and as such they limit the operation of normal ferrite core memory to a narrow temperature range.

The temperature problem in a ferrite core memory arises due to the energy that is applied for switching the core. With increase in temperature the thermal motion of magnetic domains increases and this disturbs the alignment achieved by the exchange forces. This causes the domains to deviate from their direction of easy magnetization. The purpose of this paper has been two-fold. First, the effect of temperature variation on the magnetic properties of ferrite cores was investigated together with a theoretical background. Second, a brief study of the overall performance of the memory unit using these cores was made so as to get a more reliable operation of the memory system.

2. INHERRENT CHARACTERISTICS

The stability of certain ferrite properties above the range of ambient temperature is of primary importance in computer memory operation. These properties are coercive force, squareness ratio, switching coefficient, resistivity and Curie temperature. Also the structure of the ferrite material is of importance.

It is usually found that for ferrites composed of single domain grains, the coercive force and switching speed is maximum.

Recent theories (Bloch *et al* 1964) of coercive force are based on the investigation of interaction of Bloch wall and the different types of lattice defects, each of those lattice defects determines the given dependence of coercive force on temperature (figure 1). The coercive force is also influenced by the magnetic crystalline anisotropy which again varies with the chemical composition. By appropriate substitution of cobalt it is possible to reduce the value of coercive force, but the squareness is usually affected adversely.

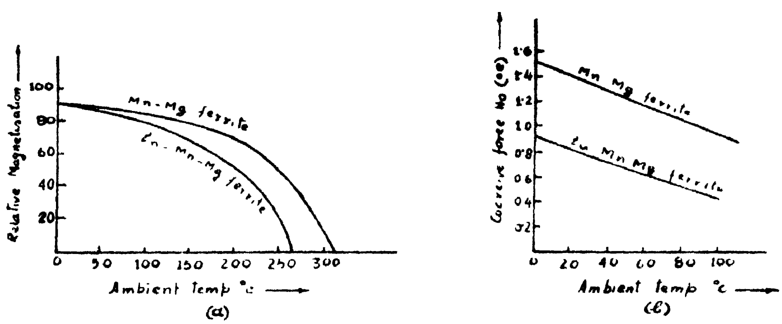

Fig. 1a. Relative magnetization as function of temperature.
Fig. 1b. Coercive force as a function of temperature for two types of ferrites.

The squareness ratio (Dutta-Majumder 1963) $R_s = B_r/B_m = H_k/H_m$ of a ferrite material is usually obtained from $B-H$ characteristics of a toroidal sample. The first ratio is called the remanence ratio and in a good squareloop ferrite it is usually 0·9 or higher at its maximum. The second ratio which is of importance to Computer Engineers, is called the disturb ratio and it decreases drastically with increasing drive field. Usually for coincident current memory the value of disturb ratio is taken slightly greater than 0·6 to allow for current drift, temperature drift and for other effects.

The other property of ferrite materials which is of importance in the memory operations is the resistivity of the materials. It is primarily determined by the ion distribution in the materials. At room temperature most manganese zinc ferrites have resistivities between about 0·01 and 10Ωm; nickel zinc ferrites normally have much higher values *e.g.*, $< 10^3 \,\Omega$ m ($10^5 \,\Omega$ cm). As ferrites are semiconductors the resistivity falls with rising temperature.

The various ferrite characteristics (table 1) discussed above are seen to have great interdependence and it is not possible to optimise simultaneously all the desired properties in any given materaial.

Table 1

composition	coercive force (Oe)	squareness ratio	switching coefficient	resistivity Ω-cm	Curie temp. °C
(1)	(2)	(3)	(4)	(5)	(6)
Lithium ferrite	2.0	0.97	0.4		670
Mg-Mn ferrite	1.2	0.94	1.0	10^6	280
Zn—Mn—Mg ferrite	0.76	0.95	0.5	2×10^7	262

3. Variation of Switching Coefficient

The application of a magnetic field causes the domain walls to come to uniform motion. The switching coefficient S_w is then proportional to the distance d between the domain walls, the friction is determined by the damping parameter β and is inversely proportional to the saturation magnetization M_s. Hence one can write.

$$S_w \propto \beta d/M_s, \qquad \ldots \quad (1)$$

This switching coefficient actually consists of two independent effects, and can be written as

$$S_w = S_{we}+S_{wl}. \qquad \ldots \quad (2)$$

where S_{we} is the contribution due to the eddy current effect and S_{wr} due to the spin relaxation. These quantities are related to the basic parameters of the material by the relation (Menyuk & Goodenough 1955)

$$S_{we} = \frac{8\pi^2\alpha M_s r_m^2}{\rho c^2 < \cos\theta >^3}, \qquad \ldots \quad (3a)$$

and

$$S_{wr} = \frac{M_s \Lambda d}{(\gamma^2 M_s^2+\Lambda^2)<\cos\theta>}\left(\frac{K}{A}\right)^{\frac{1}{2}}$$

$$\simeq \frac{\Lambda d}{\gamma^2 M_s < \cos\theta >}\left(\frac{K}{A}\right)^{\frac{1}{2}}, \qquad \ldots \quad (3b)$$

where

M_s = Saturation magnetization,

Λ = Relaxation frequency,

γ = Magnetomechanical ratio,

K = Anisotropy constant,

A = Exchange constant,

r_m = One half of the tape thickness.

ρ = Resistivity in ohm-cm,

$\cos\theta$ — Mean value of the cosine of the angle between applied field and direction of easy magnetization.

d — Maxm. distance a domain wall moves during the flux reversal,

and α — is the numerical factor $1 < \alpha < 2$ which is introduced to account for surface nucleation effect

Of the various parameters in equation 3(a), the saturation magnetization and electrical resistivity are the temperature dependent variables and in fact the switching coefficient varies with temperature as M_s/ρ. Since ferrites are semiconductor devices their resistivity falls with rising temperature. For polycrystalline ferrites the bulk resistivity arises from a combination of the crystallite resistivity and the resistivity of the crystallite boundaries. The boundary resistivity is much greater than that of the crystallinite so that the boundaries have the greater influence on the dc resistivity For high frequency operation the dc resistivity should be high to avoid the eddy current losses. It is found that over the temperature range—70 to 100 C the resistivity of manganese zinc ferrites falls by a ratio of between 30 to 100 and the corresponding figures for nickel zinc ferrites are 10^3–10^4. The resistivity ρ at an absolute temperature T is given by

$$\rho = \rho_a \exp(E/kT), \qquad \ldots (4)$$

where ρ_a is the resistivity extrapolated to $T = \infty$, E is the activation energy, k is the Boltzmann's constant. If E is to be expressed in electron—volt

$$k = 8{\cdot}62 \times 10^{-5}\text{ev}\ {}^{\circ}\text{K}^{-1}.$$

The variation of relative magnetization as a function of temperature is shown in figure 1(a). As the temperature rises from 0 K the magnetic alignment within the domains is increasingly disturbed by the thermal agitation and as a result the saturation flux density falls till the Curie point, where the magnetic alignment is completely destroyed and the material becomes paramagnetic. In manganese-zinc and nickel-zinc ferrites the larger the proportion of zinc the lower is the Curie point. Bloch (1961) using the spin theory made a prediction that for ferromagnetic material magnetization should approach its maximum value M_0 achieved at $T = 0$ in the fashion,

$$M = M_0(1 - AT^{3/2}). \qquad \ldots (5)$$

where A is a constant depending on the lattice geometry. This prediction is confirmed pretty well by experiment below the Curie temperature. Above the Curie temperature it follows an improved method of approximation called the "Bethe-Peierls Weiss" (Weiss 1948) method which is essentially a scheme wherein the interactions inside a cluster are treated rigorously, and those with atoms outside of it by means of a molecular field scheme.

Again considering the expression for switching coefficient due to spin relaxation effect, the temperature dependent parameters are Λ, K and M_s, and so far as the temperature effect is concerned one can rewrite the equation 3(b) as,

$$S_{wr} \propto \frac{\Lambda(K)^{\frac{1}{2}}}{M_s} . \quad \ldots \quad (6)$$

The variation of M_s and Λ with increasing temperature is such that it tends to increase the value of S_{wr}. But S_{wr} decreases with increasing temperature, and it is due to the fact that the value of anisotropy constant K decreases sharply with increasing temperature. The effect of temperature on magnetic anisotropy arises solely from the introduction of local deviations in the direction of magnetization. Zener (1954), however, has evolved a classical theory in which the strong temperature dependence of magnetic anisotropy is followed. The anisotropy energy should have its origin in the coupling between spin and orbital motions, which in turn are coupled to the crystallographic axes. Data given by McKeenhan (1937) shows that the anisotropy constant of an iron-nickel alloy decreases by a factor of 3·5 as it goes from 293°K to 473°K. In general the anisotropy constant is related to the magnetization by a third or fourth power law below 200°K and by a ninth power law above it.

4. Experimental Results

The equipments for the experimental part of the investigation consist of a pulse generator with the associated drive circuits and a constant temperature bath. The pulse generator was designed so that the duration and amplitude of the pulses can be adjusted. The duration of drive pulses was kept constant at a value of approximately 2·0 μsec, while the amplitude was kept to 500 mA and 600 mA for two sets of readings. The switching time and the core output voltage were measured at room temperature and at different increased temperatures upto about 100°C. The results were then plotted to obtain the characteristic curves (figures 2 and 3). In fact all magnetic materials display a gradual decrease in their magnetic properties with increasing temperature, upto Curie temperature. The Curie temperature usually varies from 300°C to 700°C for most of the square-loop ferrites. As temperature increases the core output voltage increases linearly as shown in the curves of figure 2. As would be expected the ultimate deterioration in magnetic properties at high temperatures results indeed in a reduction of output voltage. However, the curves exhibit region in which the output voltage rises as temperature increases. This effect may be attributed to several causes, among which the predominant are : (i) that the change in magnetic properties with temperature is by no means linear, and the permeability first rises to a peak and then drops rapidly as temperature increases, (ii) that as hystersis loop shrinks and coercivity decreases, the value of H produced by a fixed driving current exceeds the coercive force by larger and larger amounts. It is well accepted that the time required for flux reversal is inversely proportional to the difference between the applied field and the coercivity. Thus, although shrinkage of the B-H loop decreases ϕ. the amount of flux reversed, the phenomena of overdrive sensitivity at least partially compensates the output voltage by reducing the switching time so that $d\phi/dt$, that is the output voltage generated, may first rise and then fall as temperature increases.

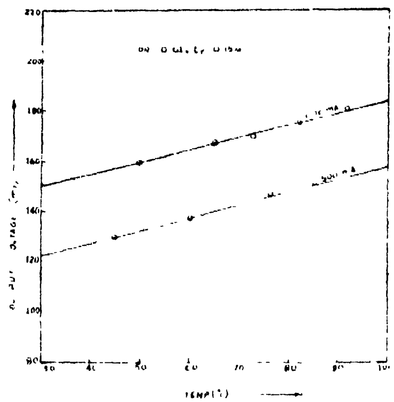

Fig. 2. Variation of output voltage with temperature.

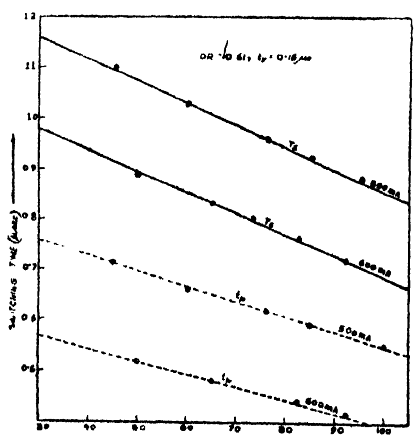

Fig. 3. Variation of T and t_p with temperature.

The variation of switching time and peaking time with temperature is shown in curves of figure 3. Both switching and peaking time of the magnetic core decrease with increasing temperature, and obviously at higher temperature the hysteresis loop shrinks and hence the time taken to traverse from one saturation point to the other is smaller and smaller. As switching time decreases, the switching coefficient also decreases in accordance with the theory discussed earlier.

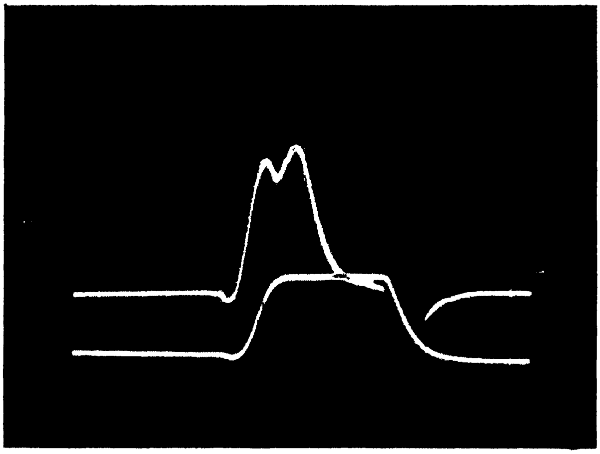

Fig. 5. Core output voltage at 30°C with a drive current of 500 mA.

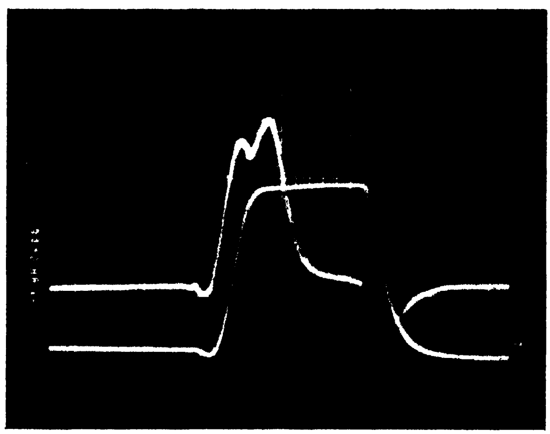

Fig. 6. Core output voltage at 60°C with a drive current of 500 mA.

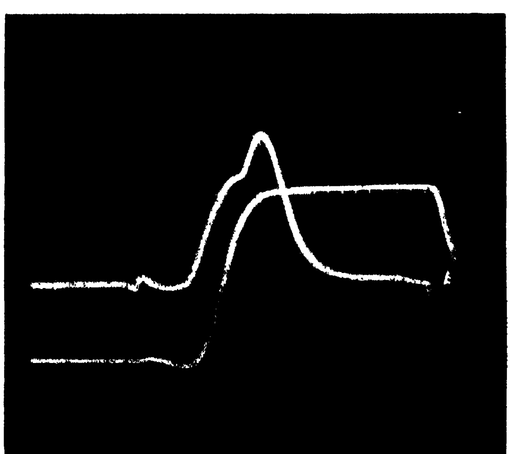

Fig. 7. Core output voltage at 75°C with a drive current of 600 mA.

The variation of switching coefficient with temperature was given by Smit & Wijn (1959) and is shown in figure 4.

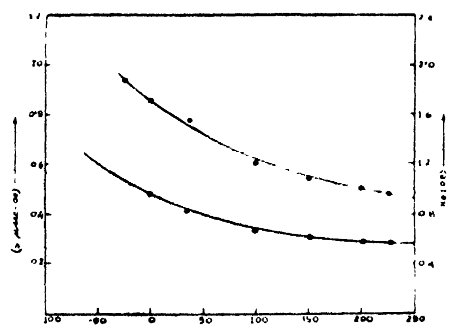

Fig. 4. The quantities S and H_0 as a function of temperature.

Figures (5), (6) and (7) show how the effect of temperature acts on the core output voltage and core switching time at 30°C and 60°C with a drive current of 500 mA. The core output voltage increased from 125 mV at 30°C to 140 mV at 60°C while the switching time has reduced slightly. Figure (5) shows the value of above parameters at a drive current of 600 mA and at a temperature of 75°C.

5. Discussion

The magnetic cores normally used in fast access memories are usually nickel ferrites and lithium ferrites, having high Curie temperatures approaching 600°C. The faster switching causes heating effect in the core material, which then deteriorate the magnetic properties and thereby increases the selection line impedance and the transmission delay. The operating environment of most of the digital data handling devices is not temperature regulated, that is in most cases there is no provision for temperature compensation of the driving currents. This might cause erroneous data transfer when sensing the memory. In developing the current tolerances for coincident current memory several assumptions are made. Usually the current tolerances are based upon the following four design criteria, namely,

(a) Effective writing of "One's"

$$2I_{w\,\min} \geqslant I_M,$$

(b) Effective writing of "Zero's"

$$2I_{w\,max} - 2I_{w\,\min} \leqslant I_T,$$

(c) The limitation of inhibit current to a value less than the switching threshold current

$$I_{z\ max} \leqslant I_T .$$

and

(d) Similar limitation on the pair of "read" currents and pair of "write" currents

$$I_{w\ max} < I_T .$$

where I_M is the minimum allowable current for full switching, I_T is the maximum allowable current for full switching, and the ratio $I_M/I_T = K$ can be taken as a core constant. Typical example for $K = 1{\cdot}5$, the allowable tolerance for the coincident current memory is approximately 9·0 per cent.

These design equations also depend upon the disturb ratio. The temperature coefficient for disturb ratio is defined as the percentage change in drive current required to maintain a constant disturb ratio which varies from 0·45 to 0·65, depending upon the material of the core and is a function of temperature. Normally for ferrite cores the disturb ratio for a constant drive decreases with increasing temperature. This effect can be thought of as if the minimum threshold current for switching decreases with increasing temperature. If the drive currents are not reduced to compensate the value of I_T, then the half selecting current take the core to larger disturbing voltages, both from half selections of "One's" and from full selection of "Zero's".

Data regarding the temperature sensitivity characteristics of ferrite core materials usually include "One" and "Zero" output voltages and the associated switching and peaking times, all varying as functions of temperature. The temperature coefficient for output voltage, defined as the percentage change in drive current required to maintain a constant UV_1, is found to be 0·4, as calculated from curves of figure 2. At room temperature the value of coercive force falls off at rates from 0·3% to 30% per degree centigrade depending upon the ferrite material. In such cases a 10°–20°C rise is often sufficient to unpair the discrimination in a large store owing to consequent reduction in coercive force value which increases the flux change in cores subjecoted to half drive pulses.

The timing of current drivers is dependent upon the core switching time. Normally, each current of the pairs of "read" and "write" pulses must be at least long enough to completely switch the core, often taken to be 1·5 times as long as the nominal switching time. The switching time of the core decreases with increasing temperature, as a result the strobing time which discriminate the signal and noise voltages changes. Hence for optimum S/N ratio the sense amplifier requires further adjustment.

TABLE 2. Summary of Memory Core Characteristics. $t_r = 0{\cdot}1$, sec and $t_d = 1{\cdot}0$ sec).

Ferrite	Dimensions (mill)	Drive Current (mA)	'One' output Voltage UV_1 (mV)	Zero output Voltage dv (mV)	peaking time t_p (sec)	Switching time T_s (sec)	Disturb ratio	Temp. coeff. of disturb ratio %	Temp. coeff. of output voltage %	Stress Sensitivity
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Mg–Mn–Zn (high Zn)	32×20×7.5	450	40	5 0	0.25	0.50	0.62	0.68	0.36	low
Mg–Mn–Zn (low Zn)	32×20×7.5	640	41	5.0	0.21	0.41	0.63	0.60	0.37	low
Cu–Mn	32×20×6.5	650	43	5.0	0.22	0.38	0.64	0.63	0.42	med.
Li–Mn	32×20×10	630	43	6.5	0.29	0.53	0.63	0.11	0.11	low
Li–Ni–Zn–Mn	30×22×8.5	550	50	4.5	0.27	0.49	0.64	0.45	0.23	high
$Ni–Fe^{2+}–Mn$	32×20×7.5	650	41	6.5	0.23	0.45	0.63	0.43	0.31	high
$Ni–Fe^{2+}$–(mag. annealed)	32×20×7.5	650	38	6.0	0.28	0.54	0.71	0.11	0.08	high

Hence for successful operation of magnetic core memories either the operation of memory at higher temperature is avoided or compensation (Ashley 1959) by the addition of a temperature sensitive element to the current driving circuit is provided and this element should be located in the same environment as the storage core.

6. Conclusions

However the speed of switching in coincident current memory is limited by the possibility of finding square-loop ferrites with a large threshold field. Although extensive investigations are being carried out to improve the basic memory elements and a series of square-loop ferrites as tabulated in table 2 are already in the market, but none is the "best" for all purposes. Efforts are continually being made to develop storage elements of smaller size, improved switching time, better squareness ratio and of a low rate of change of coercive force with temperature.

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